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13. ABSTRACT *(Maximum 200 words)*

This report describes the main research achievements during the time cited above on the research in the area of telecommunications. The main achievements include the joint turbo and modulated coding for ISI channels, precoded and vector OFDM systems with single transmit antennas and matrix modulation schemes in broadband wireless communications, and new space-time code designs and properties.

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A. **Objective**: The goal of this research is to optimally design and update modulated code without the full knowledge of the ISI channel at the transmitter with applications, in particular, in wireless communication systems.

B. **Main Research Accomplishments** We have made several research accomplishments as follows.

(i). *Joint turbo and modulated code en/decoding for ISI channels.* Turbo codes have been recently recognized as a breakthrough in error correction coding for additive white Gaussian channel (AWGN). They are used to approach the AWGN channel capacity at low channel SNR and found that they are only about 0.7dB away from the AWGN channel capacity at SNR=0.5dB. In the meantime, modulated codes (MC) were recently proposed by the PI for mitigating ISI, which are defined on the complex field and encoded after the binary-to-complex symbol mapping. The main advantage of MC is that their encoding arithmetic operations and the ISI channel arithmetic operations are all defined on the complex field and therefore can be naturally combined together, which is not possible for any current error correction coding schemes including turbo coding. The combination provides the convenience of the optimal study of the coding.

In this research, we combined the turbo coding and the modulated coding for an ISI channel, where the modulated coding is used to optimally combat the ISI while the turbo coding is used to optimally combot the AWGN. We proposed a joint turbo and modulated code encoding and decoding scheme. Surprisingly, we found that our combined coding scheme for the ISI channel $[1, 1]$ with AWGN outperforms/breaks the capacity of the AWGN channel at channel SNR -1.15dB, where the combined rate is 1/4 and the bit error rate (BER) is below 10^{-4}.

(ii). *Precoded and vector OFDM systems for single transmit antenna systems in wireless communications.* Orthogonal frequency division multiplexing (OFDM) systems have been widely used in high speed digital wireline communication systems, such as VHDSL and ADSL. In the previous project, we proposed a precoded OFDM system that may improve the performance of the OFDM systems for spectral null channels. We also proposed size $K \times 1$ vector OFDM systems that reduce the cyclic prefix length by K times compared to the conventional OFDM systems, which is significant for broadband transmissions. The precoding scheme is simply to insert one or more zeros between each two sets of K consecutive information symbols. This precoding scheme may be able to remove the spectral nulls of an ISI channel without knowing the ISI channel. In this project, we studied the precoded OFDM systems in wireless frequency-

selective Rayleigh fading channels. We analyzed the system performance and showed that our channel independent precoded OFDM system significantly outperforms the uncoded OFDM system and has much simpler complexity than the existing convolutionally coded OFDM systems.

Furthermore, in this project, we combined the "space-time coding" with precoded and vector OFDM for single antenna systems with significantly improved performance, where the concept of "space" does not exist while we simply use matrix modulations and the matrices in the matrix modulation come from the space-time code designs. What I want to emphasize here is as follows. Space-time coding has become an active research topic in wireless communications because of the potential usefulness of multiple antenna systems and space-time codes can be used for resisting the fading. However, multiple antennas may cost significantly more single antenna and it is the reason why industry has not chosen to use multiple antenna systems. On the other hand, the vector OFDM I proposed is for single antenna systems and the multipath become the virtual multiple antennas. I believe such combination may make space-time codes useful in industry.

(iii). *Differential space-time modulation.* Differential space-time modulation has been recently proposed in the literature for multiple antenna systems over Rayleigh fading channels, where neither the transmitter nor the receiver knows the fading coefficients. For the practical success of the differential space-time modulation, it has been shown critical to design unitary space-time signal constellations with large diversity product which is a primary property for the signal constellations to have good performance in high signal-to-noise ratio (SNR) scenarios.

In this research, we focused on the design of unitary signal constellations for differential space-time modulation with double transmit antennas. By using the parametric form of a two by two unitary matrix, we presented a class of unitary space-time codes called *parametric codes* and show that this class of unitary space-time codes lead to a five-signal constellation with the largest possible diversity product and a sixteen-signal constellation with the largest known diversity product. Although the parametric code of size sixteen is not a group by itself, we showed that it is a subset of a group of size thirty two.

We also used large diversity sum of unitary space-time signal constellations as another significant property for the signal constellations to have good performance in low SNR scenarios. The newly introduced unitary space-time codes can lead to signal constella-

tions with sizes of five and nine through sixteen that have the largest possible diversity sums. Subsequently, we constructed a four-signal constellation which has both the largest possible diversity product and the largest possible diversity sum. Three unitary signal constellations with the largest possible diversity sums were also built for the constellation sizes of six, seven and eight, respectively. Furthermore, by using a number of existing results in sphere packings and spherical codes, we obtained several upper and lower bounds on the largest possible diversity product and the largest possible diversity sum that unitary signal constellations of any size can achieve.

Differential space-time modulation for multiple antenna communication systems has been recently proposed for frequency-non-selective fading channels in the literature. We proposed an equalization technique for differential space-time modulation when intersymbol interference (ISI) presents, such as frequency-selective fading. We incorporated multiple block decision feedback detection in a linear equalization. Under the minimum mean square error (MMSE) criterion, the RLS algorithm was derived. Our simulations show that the equalization combined with multiple block decision feedback detection works well for both fixed ISI channels and fading channels with small fading rate $f_d T_s = 10^{-5}$.

(iv). *Orthogonal space-time block codes.* Space-time codes from orthogonal designs have two advantages, namely, fast maximum-likelihood (ML) decoding and full diversity. Rate 1 real (PAM) space-time codes (real orthogonal designs) for any transmit antennas have been constructed from the real Hurwitz-Radon families, which also provides rate 1/2 complex (QAM) space-time codes (complex orthogonal designs) for any number of transmit antennas. Rate 3/4 complex orthogonal designs (space-time codes) for 3 and 4 transmit antennas existed in the 20's in the literature but no high rate ($> 1/2$) complex orthogonal designs have existed for transmit antenna numbers $n \geq 5$ since then. We recently presented rate 7/11 and rate 3/5 complex orthogonal designs for 5 and 6 transmit antennas, respectively. We also presented some rate 1/2 complex orthogonal designs of small block sizes.

From the Hurwitz-Radon theory in the 20's, it is known that real orthogonal space-time block codes (or real orthogonal designs) can achieve the maximum possible rate of one for *any number* of transmit antennas using any arbitrary *real* constel lation and for *two* transmit antennas using any arbitrary *complex* constellat ion. It is also known that the rate of the square complex orthogonal designs for more than two transmit antennas is less than one, i.e., in the case when the time delay is the same as the number of transmit

antennas. However, it has been not clear for non-square complex orthogonal designs for an arbitrary time delay. In fact, it has been an open problem in the literature. We recently proved that there does *not* exist rate one complex orthogonal space-time block code (or complex orthogonal designs) for transmission with *more than two* antennas using any arbitrary *complex* constellation no matter what a time delay is used.

(v). *Polynomial ambiguity resistant precoders (PARP) for mitigating ISI without knowing the channel.* We have previously developed a new family of filterbank precoders called PARP, which can be used at the transmitter such that the receiver is able to blindly recover the information sequence without knowing the ISI channel. There are two kinds of PARP: PARP and strong PARP, where PARP is for the input signal recovery while the strong PARP is for both the input signal and the channel recovery. In this year, we have shown that a filterbank precoded system has the blind identifiability if and only if the filterbank precoder is PAPR. We have also shown that a filterbank precoder of size $(K+1) \times K$ is PARP if and only if it is also strong PARP. Some new characterizations and constructions of (strong) PARP have been also obtained.

(vi). *A new multirate detection algorithm.* Information transmission with multiple rates is an important feature in the current and future digital communication systems. As an example, in current U.S. digital cellular communication standard, the forward link (from base station to mobiles) has four different rates of the speech transmission according to the speech activities at the transmitter. At the receiver, the correct data rate is desired for the decoder to correctly d ecode the information. The speech encoding rates vary from frame to frame. In each frame, the symbols a re repeated to keep a fixed data rate. The times one symbol repeats in each fram e depend on the information rate. In this research, we have proposed a new multi-rate detection algorithm, where the decision thresholds are independent of the SNR in an AWGN channel.

(vii). *Other Main Results in Theory and Applications in Radar and Communications of Wavelets, Filterbanks, and Joint Time-Frequency Analysis and Synthesis*

> A new synthetic aperture radar (SAR) imaging method (called MF-SAR) of ground moving targets was proposed, where a linear antenna array is used and the transmitter transmits multiple frequency signals. With this method, we show that a moving target with any velocity can be correctly located. In this work, we developed a robust Chinese Remainder Theorem (CRT), where the modulos may not be integers for unwrapping the phase.

A new three dimensional ISAR imaging method of manueuvering targets was obtained by using three receivers. With this method, a three dimensional target can be imaged.

Hidden Markov models in the wavelet domain with image processing applications. We obtained several other signal processing results including new applications of hidden Markov models in the wavelet domain to image denoising, segmentation, characterization, and synthesis.

C. **Significance**: Our proposed joint turbo and modulated coding for ISI channel has outperformed the AWGN channel capacity at low channel SNR. The proposed channel independent precoded OFDM and vector OFDM system using single transmit antenna is robust to spectral-nulls in wireless frequency-selective fading channels, increase the throughput, and robust to fading. These will have significant applications in both wireless and wireline digital communications industries. In a way, orthogonal space-time block codes can be formulated as a class of block MC since their linearity in the encoding. Space-time coding plays an important role in multi-antenna systems to increase the capacity. The results we obtained in space-time coding are among the best known results that are important not only in theory but also in practical space-time code designs. We believe that these results will significantly impact the community.

D. **Publications, Abstracts, Technical Reports, and Patent Disclosures or Applications** (last 12 months):

Published Books

1. Xiang-Gen Xia, *Modulated Coding for Intersymbol Interference Channels*, Marcel Dekker, New York, Oct. 2000.

Published and Accepted (Refereed) Journal Publications

1. X.-B. Liang and X.-G. Xia, "Unitary Signal Constellations for Differential Space-Time Modulation with Two Transmit Antennas: Parametric Codes, Optimal Designs, and Bounds," *IEEE Trans. on Information Theory*, to appear.
2. X.-G. Xia, "Differential En/Decoding Orthogonal Space-Time Block Codes with APSK Signals," *IEEE Communications Letters*, to appear.

3. X.-G. Xia, G. Wang, and V. C. Chen, "A Quantitative Signal-to-Noise Ratio Analysis for ISAR Imaging Using Joint Time-Frequency Analysis –Short Time Fourier Transform," *IEEE Trans. on Aerospace and Electronics Systems,* to appear.
4. G. L. Fan and X.-G. Xia, "A Joint Multi-context and Multiscale Approach to Bayesian Image Segmentation," *IEEE Trans. on Geoscience and Remote Sensing,* Dec. 2001.
5. P. Fan and X.-G. Xia, "Two modified discrete chirp-Fourier transforms," *Sciences in China, Series D,* Oct. 2001.
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7. G. L. Fan and X.-G. Xia, Image denoising using local contextual hidden Markov model in the wavelet domain, *IEEE Signal Processing Letters*, May 2001.
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9. X.-G. Xia, Dynamic range of the detectable parameters for polynomial phase signals using multiple lag diversities in high-order ambiguity functions, *IEEE Trans. on Information Theory*, May 2001.
10. P. Fan and X.-G. Xia, A noncoherent coded modulation for 16QAM, *IEEE Trans. on Communications*, April 2001.
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17. X.-G. Xia, Discrete chirp-Fourier transform and its application in chirp rate estimation, *IEEE Trans. on Signal Processing*, Nov. 2000.

18. G. Wang and X.-G. Xia, An iterative algorithm for direction of arrival estimation with wideband chirp signals, *IEE Proceedings Radar, Sonar and Navigation*, Oct. 2000.

19. X.-G. Xia and G. Zhou, On optimal ambiguity resistant precoders in ISI/multipath cancellation, *IEEE Trans. on Circuits and Systems II*, August 2000.

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21. X.-Q. Gao, Z.-Y. He, and X.-G. Xia , The theory and implementation of arbitrary-length linear-phase cosine-modulated filter bank, *Signal Processing*, vol.80, no.5, May, 2000.

22. P. Fan and X.-G. Xia, Joint turbo coding and modulated coding for channel with intersymbol interference, *IEEE Trans. on Consumer Electronics*, vol.46, May 2000.

23. X.-G. Xia, An efficient frequency estimation algorithm from multiple undersampled waveforms, *IEEE Signal Processing Letters*, Feb. 2000.

24. X.-G. Xia and H. Liu, Polynomial resistant precoders: theory and applications in ISI/multipath cancellation, *Circuits, Systems and Signal Processing*, vol.19, no.2, pp.71-98, 2000.

Submitted (Refereed) Journal Publications

25. W. Su and X.-G. Xia, "On space-time block codes from complex orthogonal designs," submitted to *Wireless Person. Comm.*.

26. W. Su and X.-G. Xia, "Signal Constellations for Quasi-Orthogonal Space-Time Block Codes with Full Diversity," submitted to *IEEE Trans. on Information Theory*.

27. A. Song and X.-G. Xia, "Decision Feedback Differential Detection for Differential Orthogonal Space-Time Modulation with APSK Signals over Frequency-non-Selective Fading Channels," submitted to *IEEE Trans. on Wireless Communications*.

28. X.-B. Liang and X.-G. Xia, "Fast Differential Unitary Space-Time Demodulation via Square Orthogonal Designs" submitted to *IEEE Trans. on Wireless Communications.*

29. A. Song and X.-G. Xia, "Decision Feedback Differential Detection for Differential Space-Time Modulation over Flat Rayleigh Fading Channels," submitted to *Journal of Communications and Networks.*

30. Y. Wu, X.-G. Xia, Q. Zhang, and W. Zhu, "Collision Probability and Throughput Analysis in a DS-CDMA Wireless Network," submitted to *IEEE Trans. Veh. Technology.*

31. H. Zhang, X.-G. Xia, Q. Zhang, and W. Zhu, "Precoded OFDM with Adaptive Vector Channel Allocation for Scalable Video Transmission over Frequency-Selective Fading Channels," submitted to *IEEE Trans. on Mobile Computing.*

32. Y.-J. Zhang and X.-G. Xia, "A minmax design of transceiver filterbank design for ISI channel," submitted to *IEEE Trans. Signal Processing.*

33. W. Su and X.-G. Xia, "Two Generalized Complex Orthogonal Space-Time Block Codes of Rates 7/11 and 3/5 for 5 and 6 Transmit Antennas," submitted to *IEEE Trans. on Information Theory.*

34. X.-B. Liang and X.-G. Xia, "Nonexistence of Rate One Space-Time Block Codes from Generalized Complex Linear Processing Orthogonal Designs for More than Two Transmit Antennas," submitted to *IEEE Trans. on Information Theory.*

35. G. Wang, A. Song, and X.-G. Xia, "Linear Equalization Combined with Multiple Block Decision Feedback Detection for Differential Space-Time Modulation," *EURASIP J. Applied Signal Processing.*

36. G. Wang and X.-G. Xia, "Orthogonal Space-Time Coding for CPM System with Fast Decoding," submitted to *IEEE Trans. on Information Theory.*

Conference Proceeding Publications

1. H. Wang and X.-G. Xia, "Upper Bounds of Rates of Space-Time Block Codes from Complex Orthogonal Designs," Proceedings of the International Symp. Information Theory, Lausanne, Switzerland, June 30-July 5, 2002.

2. X.-G. Xia, "Differentially En/Decoded Orthogonal Space-Time Block Codes with APSK Signals," Proceedings of the International Symp. Information Theory, Lausanne, Switzerland, June 30-July 5, 2002.

3. G. Wang and X.-G. Xia, "An Orthogonal Space-Time Coding for CPM Systems," Proceedings of the International Symp. Information Theory, Lausanne, Switzerland, June 30-July 5, 2002.

4. G. Wang and X.-G. Xia, "Orthogonal Space-Time Coding for CPM System with Fast Decoding," Proceedings of ICC'02, New York City, April 28-May 2, 2002.

5. H. Zhang, X.-G. Xia, Q. Zhang, and W. Zhu, "Precoded OFDM with adaptive vector channel allocation for scalable video transmission over frequency-selective fading channels," Proceedings of ICASSP02, Orlando, FL, May, 2002.

6. W. Su and X.-G. Xia, "Quasi-orthogonal space-time block codes with full diversity," Proc. of SPIE, Seattle, WA, July 2002.

7. X.-G. Xia, G. Wang, and V. C. Chen, "A Quantitative SNR Analysis of Linear Chirps in the Continuous-Time Short-Time Fourier Transform Domain with Gaussian Windows," Proc. of ICASSP01, Salt Lake City, May 2001.

8. G. Wang, X.-G. Xia, and V. C. Chen, Radar imaging of moving targets in foliage using polarimetric multi-frequency antenna array SAR, Proceedings of IEEE Radar Conference, Atlanta, May 1-3, 2001.

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11. X.-B. Liang and X.-G. Xia, Some unitary space-time codes for differential space-time modulation, Proc. of 34th Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, Nov. 2000.

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15. G. Fan and X.-G. Xia, Multiscale texture segmentation using hybrid contextual labeling tree, 2000 IEEE International Conference on Image Processing, Vancouver, CA, Sept. 2000.

16. G. Fan and X.-G. Xia, Wavelet-based image denoising using hidden Markov models, 2000 IEEE International Conference on Image Processing, Vancouver, CA, Sept. 2000.

17. P. Fan and X.-G. Xia, A Modified Discrete Chirp-Fourier Transform Scheme, International Conference on Signal Processing, Beijing, China, Aug. 2000.

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Princeton University, March, 2000.

26. X.-G. Xia, G. Wang, and P. Fan, Space-time modulated codes for memory channels, Proceedings of SAM 2000, Boston, March 2000.
27. X.-G. Xia, Multiple frequency estimation in the undersampled waveforms, Proceedings of SPIE, Orlando, April, 2000.

F. Collaborators:

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G. Post Doctors and Students Supported and Partially Supported by the Grant

Post Doctors:

Dr. Haiquan Wang and Dr. Xiao Ma

Graduate Students:

Mr. Weifeng Su, and Mr. Alan Yongjun Zhang

H. Appendix: Some Publications